

The *XMM-Newton*/*Chandra* monitoring campaign of the Galactic center region

Description of the program and preliminary results[★]

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ABSTRACT

We present the first results of our X-ray monitoring campaign on a 1.7 square degree region centered on Sgr A* using the satellites *XMM-Newton* and *Chandra*. The purpose of this campaign is to monitor the behavior (below 10 keV) of X-ray sources (both persistent and transient) which are too faint to be detected by monitoring instruments aboard other satellites currently in orbit (e.g., *Rossi X-ray Timing Explorer*; *INTEGRAL*). Our first monitoring observations (using the HRC-I aboard *Chandra*) were obtained on June 5, 2005. Most of the sources detected could be identified with foreground sources, such as X-ray active stars. In addition we detected two persistent X-ray binaries (1E 1743.1–2843; 1A 1742–294), two faint X-ray transients (GRS 1741.9–2853; XMM J174457–2850.3), as well as a possible new transient source at a luminosity of a few times 10^{34} erg s^{−1}. We report on the X-ray results on these systems and on the non-detection of the transients in follow-up radio data using the Very Large Array. We discuss how our monitoring campaign can help to improve our understanding of the different types of X-ray transients (i.e., the very faint ones).

Key words. accretion, accretion disks – binaries: close – X-rays: binaries

1. Introduction

Many X-ray sources (the so-called X-ray transients) exhibit orders of magnitude variability in their X-ray luminosities. Normally they are too dim to be detected and they are only discovered when they experience one of their bright outbursts.

The brightest transients can be identified with Galactic neutron stars and black holes accreting matter from a companion star (the “X-ray binaries”). The outbursts are ascribed to a huge increase in the accretion rate onto the compact object. Several other types of sources can also manifest themselves as X-ray transients (e.g. accreting white dwarfs, magnetars, γ -ray bursts, flare stars, young stellar objects, active binaries), however, their peak luminosities are many orders of magnitude lower than

[★] Appendix A is only available in electronic form at
<http://www.edpsciences.org>

those of the transient X-ray binaries (except for γ -ray bursts and bursts from magnetars). One usually refers only to transient X-ray binaries when talking about X-ray transients.

1.1. Classifying the X-ray transients

Early satellites were mostly able to detect only the brightest transients. As the instruments became more sensitive, fainter transients were found which exhibit qualitatively different behavior from the brighter systems. Consequently, in this paper we classify the different X-ray transients based on their maximum observed peak X-ray luminosities (from here on we will quote 2–10 keV luminosities unless otherwise noted):

Bright to very bright X-ray transients: these transients have peak X-ray luminosities of 10^{37-39} erg s $^{-1}$ (e.g., Chen et al. 1997). Monitoring campaigns with several satellites (e.g., *BeppoSAX*, *RXTE*, *INTEGRAL*; see, e.g., In't Zand 2001; Levine et al. 1996; Swank & Markwardt 2001; Revnivtsev et al. 2004; see In't Zand 2001, for an overview of past and current monitoring campaigns focusing on the Galactic center region) have been very successful in discovering many such bright X-ray transients and monitoring their X-ray properties. Intensive studies of the large amount of available data have yielded a good understanding of their behavior and it has been found that a large fraction of them harbor accreting black holes if they accrete from a companion star with a mass $\lesssim 1$ solar mass, but a neutron star if the companion has a mass $\gtrsim 10$ solar masses. In systems with a low-mass companion (the low-mass transients), the mass transfer occurs because the donor star overflows its Roche-lobe. To explain the outbursts, the disk instability model is the most widely accepted (e.g., Lasota 2001). In the massive transients the mass transfer occurs because of the strong stellar wind of the companion star or through a decretion disk. The most common type are the so-called Be/X-ray transients in which matter is accreted from the circumstellar decretion disks around rapidly spinning B or sometimes late O-type stars. The physics behind the irregular outbursts observed for the bright high-mass transients are not yet fully understood but it has been suggested that these systems might be Be/X-ray binaries which have relatively low eccentricities (e.g., Okazaki & Negueruela 2001).

Faint X-ray transients: these transients have peak X-ray luminosities of 10^{36-37} erg s $^{-1}$. Although the faint high-mass transients also contain mostly neutron-star accretors, their outbursts are markedly different from their brighter siblings since the faint outbursts occur usually in series separated by the orbital period while the brighter outbursts do not repeat every orbit, clearly indicating different physics involved (Okazaki & Negueruela 2001). It is thought that these periodic outbursts occur when an accretor is in a wide eccentric orbit around a Be star and only at minimum distance from the companion does the accretor come inside the decretion disk of the Be star where it is able to accrete matter and thus become X-ray active (e.g., Okazaki & Negueruela 2001). Similarly, several detections of low-mass faint transients have been made

in the past (e.g., Sunyaev 1990; Pavlinsky et al. 1994), but only recently it was realized that they might form a distinct class from the brighter low-mass systems (Heise et al. 1999; In't Zand 2001). This realization came when many such faint low-mass systems were detected by the Wide Field Cameras (WFC) aboard *BeppoSAX*. Several global characteristics of the faint low-mass transients sets them apart from the brighter systems. First, contrary to what is observed for the brighter low-mass systems, a very large fraction of the faint ones contain neutron-star accretors as determined by the detection of type-I X-ray bursts or millisecond X-ray pulsations¹ from them. Second, their Galactic distribution is different from that of the brighter systems (Cornelisse et al. 2002a), with the faint low-mass transients more concentrated toward the Galactic center. King 2000 argued that the faint low-mass transients are indeed different from the bright systems and that they are mainly neutron star X-ray binaries in very compact binaries with orbital periods < 80 min. However, clearly not all systems have such short orbital period since, e.g., the faint transients and millisecond X-ray pulsars SAX J1808.4–3658, XTE J1814–338, and IGR J00291+5934 have periods > 80 min. Also not all systems harbor neutron stars since the faint transient XTE J1118+480 is a strong black hole candidate (Wagner et al. 2001).

Very faint X-ray transients (VFXTs): these transients have peak X-ray luminosities of 10^{34-36} erg s $^{-1}$. Until recently, only limited evidence was available for the existence of this class because detecting such very faint transients is challenging due to sensitivity and/or angular resolution limits of many X-ray instruments. Despite the difficulties in finding VFXTs, pointed observations with relatively sensitive X-ray satellites (e.g., *Granat*; *ASCA*) resulted in the detection of several VFXTs near the Galactic center (e.g., Pavlinsky et al. 1994; Torii et al. 1998; Maeda et al. 1996). More recently, a significant number of systems have been found (Sidoli et al. 1999; Hands et al. 2004; Porquet et al. 2003; Sakano et al. 2005; Munro et al. 2003b), thanks to the sensitive *Chandra* and *XMM-Newton* X-ray satellites, supporting the claim (e.g., Sakano et al. 2005) that a class of VFXTs exists in our Galaxy. It is very likely that these VFXTs are accreting neutron stars and black holes since only one accreting white dwarf has exhibited outbursts above 10^{34} erg s $^{-1}$ (Watson et al. 1985). For this reason we use 10^{34} erg s $^{-1}$ as the lower luminosity border for the VFXTs class (see also Verbunt et al. 1984). In Sect. 1.2 we discuss the VFXTs further.

Our classification of *bright to very bright*, *faint*, and *very faint* X-ray transients is somewhat arbitrary and it is clear that systems straddling these classes do exist. For example, the neutron star X-ray transient in the globular cluster NGC 6440 was classified as a faint X-ray transient (In't Zand et al. 1999)

¹ It is interesting to note that all but one of the seven currently known accreting millisecond X-ray pulsars (see Wijnands 2004, for a review) are faint X-ray transients. The one which is not a faint transient (XTE J1751–305; peak X-ray luminosities of a few times 10^{37} erg s $^{-1}$) had a very short outburst duration (e-folding time of only ~ 7 days) resulting in a low time-averaged accretion rate similar to the other accreting millisecond pulsars.

but later it was found to also exhibit bright X-ray outbursts (Kaaret et al. 2003). Furthermore, the bright neutron star X-ray transient SAX J1747.0–2853 (e.g., Werner et al. 2004) was seen on several occasions at luminosities of only a few times 10^{35} erg s⁻¹ (e.g., Wijnands et al. 2002). If the bright outbursts of this source had been missed because, for example, no X-ray satellite was pointed in the source direction, then it would have been misclassified as a VFXT. Nevertheless, in this paper such a classification will prove quite useful in talking about the different types of transients.

Recently, another type of accreting neutron star has been identified in the Galaxy: the so-called “burst-only sources” (Cornelisse et al. 2002a). The burst-only sources are a group of nine objects detected by the *BeppoSAX*/WFC when they exhibited a type-I X-ray burst. No detectable accretion emission around the bursts could be detected with that instrument, with typical upper limits on the accretion luminosities of the order of 10^{36} erg s⁻¹. Subsequent X-ray observations of these systems using a variety of satellites revealed that one source is a persistent X-ray source at very faint luminosities (In ’t Zand et al. 2005), two are faint X-ray transients (e.g., Cornelisse et al. 2002b), and one is a VFXT (e.g., Hands et al. 2004). The other five sources could not yet be classified, although they are all X-ray transients since follow-up observations with *Chandra* could not detect any persistent accretion luminosities from them (Cornelisse et al. 2002b). Presumably, they experienced their X-ray bursts during brief accretion outbursts which had peak luminosities below $\sim 10^{36}$ erg s⁻¹. Therefore, these systems are good candidates to be classified as VFXTs, although definitive proof has to come from detecting these systems during such very faint outbursts (see also Cornelisse et al. 2004 for a discussion on the classification of burst-only sources).

1.2. VFXTs in more detail

Currently, little is known about the properties of the VFXTs due to the low number of systems known and the scarcity of observations during their outburst episodes. Some of them might be intrinsically bright transients at large distances; however, many are observed near the Galactic center, indicating source distances of ~ 8 kpc and therefore very low peak intrinsic luminosities. In addition, some VFXTs might be intrinsically brighter than observed due to inclination effects (e.g., Munro et al. 2005), but this can be argued for only a small fraction of the VFXTs (see the appendix; see also King & Wijnands 2006). Therefore, we consider it likely that most VFXTs indeed have very faint intrinsic X-ray luminosities.

The characteristics of the VFXTs (e.g., their spectra, their outburst light curves, timing properties; e.g., Sakano et al. 2005; Munro et al. 2005a; Torii et al. 1998) indicate that they are not a homogeneous class of sources but that different types of accreting neutron stars and black holes show themselves as VFXTs. The detection of slow pulsations in some VFXTs (e.g., Torii et al. 1998) indicates that at least some VFXTs could have a high mass donor star since a slow

X-ray pulsar is usually associated with high-mass X-ray binaries. The detection of a significant number of high-mass systems would be very important since the currently identified (brighter) systems form likely only a small fraction of the total Galactic population of high-mass X-ray binaries. However, it is possible that some of these systems might in fact not be high-mass X-ray binaries but instead relatively close-by accreting magnetic white dwarfs (i.e., the intermediate polars). From the X-ray data it is difficult to ascertain the exact nature of these systems and identifications of their optical or IR counterparts are needed to distinguish the high-mass X-ray binary systems from the white dwarf systems.

No significant pulsations have so far been detected for the other VFXTs. More information about the nature of these systems could be obtained by studying them in optical or infrared. However, none of the VFXTs has so far been detected at optical or infrared wavelengths. For the VFXTs in the Galactic center region it was found that they harbor companions fainter than B2 IV stars (Munro et al. 2005a). Therefore, it is likely that a significant fraction of the VFXTs are neutron stars and black holes accreting matter at a very low rate from a low-mass companion star. Moreover, at least one VFXT has exhibited type-I X-ray bursts (SAX J1828.5–1037; Cornelisse et al. 2002a; Hands et al. 2004) which are usually identified with low-mass X-ray binaries. Such low-mass X-ray binaries have very low time-averaged accretion rates, which could become a challenge for our understanding of their evolution (King & Wijnands 2006).

To improve on the limited amount of knowledge about the observational properties of VFXTs, monitoring campaigns are required with instruments which:

- are sensitive enough to detect the very faint X-ray luminosities of these systems;
- have a large field-of-view (FOV) to monitor a large region allowing for the discovery and monitoring of many systems;
- have rapid data turn-around time to allow fast follow-up observations at all wavelengths to study the VFXTs when they are still active;
- have (sub-)arcsecond resolution to limit source confusion and to allow for unique determination of the counterparts at other wavelengths which will help to establish the nature of the systems (e.g., IR observations might help to determine the type of companion star).

Such a monitoring instrument does not exist and in practice might be difficult to achieve since, for example, a large FOV and very good sensitivity are usually mutually exclusive. Fortunately, *XMM-Newton* and *Chandra* are excellent to perform such a monitoring program but only within a limited FOV. Therefore, we have secured such a program using both satellites for a limited region close to Sgr A*. This region was chosen for two reasons: there is a high concentration of stars along the line of sight and most known VFXTs have been detected in this region (e.g., Munro et al. 2005a). We will first describe the details of the program and then present some initial preliminary results.

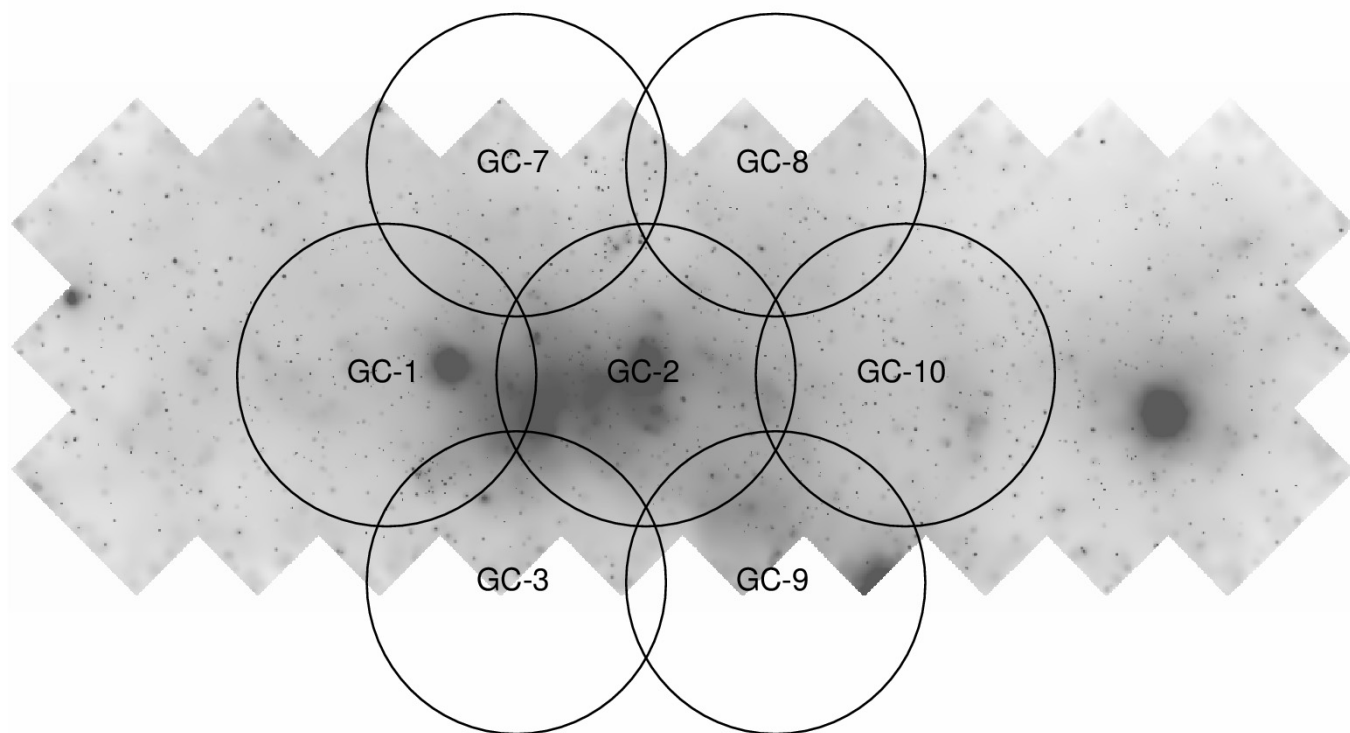


Fig. 1. Field-of-view of our monitoring campaign in Galactic coordinates. The circles indicate the *XMM-Newton*/MOS FOV which is similar to the *Chandra*/HRC-I FOV. The FOV is over-plotted on the *Chandra* Galactic center survey data as presented by Wang et al. (2002), which is centered around Sgr A* and covers a region of approximately $1^\circ \times 2^\circ$. The “field name” (see Table 1) of each pointing is indicated.

2. Description of our program

In proposal cycle 4 of *XMM-Newton*, we have secured a program using this satellite in combination with the *Chandra* X-ray Observatory to monitor a 1.7 square degree region centered around Sgr A*. The FOV of our program is shown in Fig. 1. We will have 4 X-ray epochs (two with *XMM-Newton* and two with *Chandra*) with each epoch consisting of seven observations (their pointing directions are indicated in Fig. 1). Each pointing lasts ~ 5 ks and will reach an overall sensitivity of $\sim 5 \times 10^{33}$ erg s $^{-1}$ (at 8 kpc; from here on we assume a distance of 8 kpc when quoting X-ray luminosities) for the *Chandra* observations to an order of magnitude better for the *XMM-Newton* observations. The FOVs of the different pointings overlap by several arcminutes (Fig. 1) to compensate for the loss in sensitivity toward the edge of the FOV of the instruments. For the *Chandra* pointings we have chosen to use the HRC-I detector because it has the largest FOV of any instrument aboard *Chandra* (the FOV of the HRC-I is approximately equal to the FOV of the instruments aboard *XMM-Newton*), although this comes at a loss of sensitivity for hard sources and the loss of any spectral information. All detectors will be on during the *XMM-Newton* observations but we will mostly focus on the data obtained with the EPIC detectors (the two MOS and the pn chips). The RGS will only be useful when a single bright source is in the FOV.

The purpose of our monitoring campaign is to study the variability behavior of the transient and persistent sources in the survey region at levels not reachable by other monitoring

instruments in orbit. Although our interests focus on the accreting neutron stars and black holes in the FOV, our campaign will also be used to study the X-ray properties of X-ray active stars, dense star clusters (e.g., the Arches cluster), flares from Sgr A*, accreting white dwarfs, and any other object in the FOV which might exhibit persistent or transient X-ray emission at levels detectable during our observations. The different observation epochs are separated in time from each other by at least one month so that we can monitor the X-ray behavior of the detected sources on timescales of about 1 month to almost a year. The first epoch data were gathered on 5 June 2005 (*Chandra*) and the remaining three epochs are currently scheduled for the week of 17–24 October 2005 (*Chandra*), and at the end of February 2006 and early April 2006 (*XMM-Newton*). Here we report on the initial results obtained during the first epoch *Chandra* data.

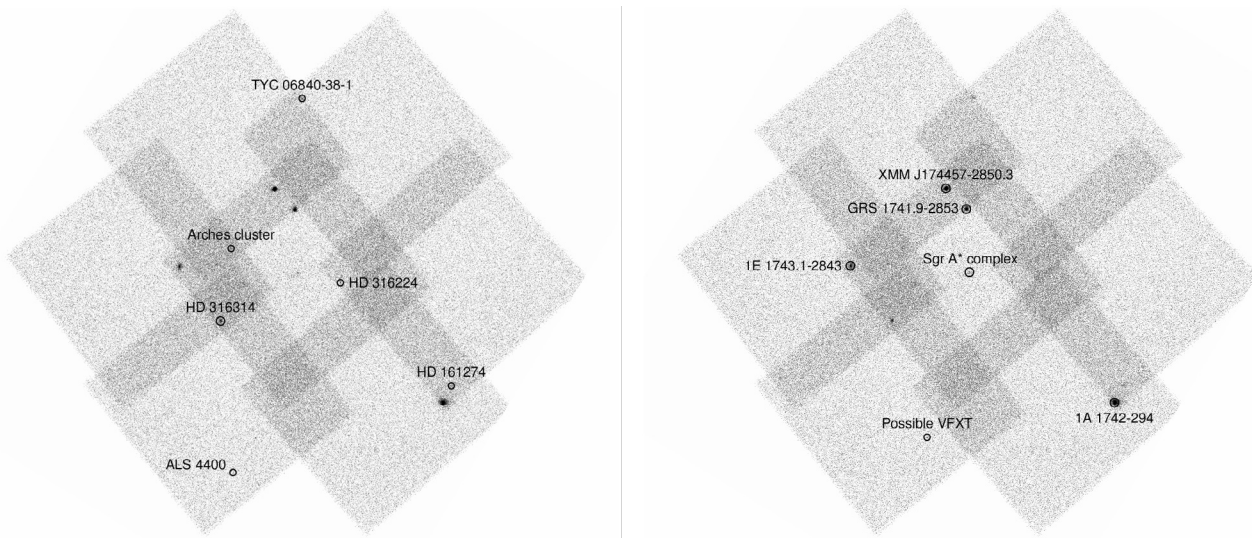
3. Data analysis

The first data of our monitoring campaign were obtained on 5 June 2005, using the *Chandra* satellite (see Table 1 for a log of the observations) and the HRC-I detector. We processed the data using the *Chandra* CIAO tools (version 3.2.1) and the standard *Chandra* analysis threads². We checked for background flares during our observations, but none were found, allowing us to use all available data. We merged the 7 different HRC-I observations into one image which we show in Fig. 2. Clearly, several bright sources are visible by eye. We used the tool

² Available from <http://cxc.harvard.edu/ciao/>

Table 1. Log of the *Chandra* observations for epoch 1.

Field name	ObsID	Date (June 5, 2005, UTC)	Exposure (ks)	Instrument
GC-1	6188	01:44–03:32	5.08	HRC-I
GC-2	6190	03:32–05:05	5.15	''
GC-3	6192	05:05–06:37	5.14	''
GC-7	6194	06:37–08:09	5.14	''
GC-8	6196	08:09–09:41	5.14	''
GC-9	6198	09:41–11:13	5.15	''
GC-10	6200	11:13–13:08	5.15	''
GRS 1741.9–2853 & XMM J174457–2850.3	6311	02:04–03:40 July 1	4.01	ACIS-I ''

**Fig. 2.** The merged image of the 7 *Chandra*/HRC-I observations. *Left panel:* the Arches cluster and a sub-set of the detected foreground objects are indicated (only those stars which are known in Simbad are labeled). *Right panel:* the detected X-ray binaries as well as the possible VFXT. Also indicated is the complex X-ray emission around Sgr A*.

wavdetect to search for point sources in our data and to obtain the coordinates of each source that was detected. We ran the tool on the combined image as well as on each individual observation. Due to variations in the size and shape of the point-spread-function as a function of offset angle from the pointing directions, we ran *wavdetect* on images with different binning factors. We are still exploring ways to optimize our detection method so it is likely that in our final analysis we will find more sources than the ones we report on in this paper. However, we expect that in the current analysis we are complete for sources with inferred X-ray luminosities $>10^{34}$ erg s $^{-1}$.

The errors on the source positions are difficult to estimate for the sources found at relatively large offset angles. The asymmetries in the point-spread-function at large off-axis angles can result in large systematic uncertainties when using *wavdetect* (e.g., Hong et al. 2005). We are pursuing extensive simulations to investigate the effects on the positional errors for a large range of offset angles as well as different source luminosities. A similar investigation has already been performed for the *Chandra*/ACIS-I combination by Hong et al. (2005). Although they investigated the ACIS-I (and not the HRC-I), used only offset angles up to 10' (instead of $>20'$ as we sometimes encounter), and focused mainly on the faint sources, we

will use their results as a first order approximation on the accuracy of the positions we obtain using *wavdetect*. We use Eq. (5) in Hong et al. (2005) to estimate the uncertainties in our positions. If the sources were detected in multiple observations, we only give the positions and their errors obtained from the data set in which the sources had the smallest offset in order to minimize systematic uncertainties. However, we urge caution when using our positional uncertainties.

For each detected source we extracted the background corrected count rate from the images using the standard CIAO tools for the full energy range of the HRC-I (0.08–10 keV). The count rates obtained can be converted into fluxes using PIMMS³, assuming particular spectral models and values for the interstellar absorption. Again, the analysis is complicated because many sources are detected at large off-axis angles and vignetting becomes a serious issue. It is currently difficult to correct the count rates for vignetting because the effects depend strongly on both the off-axis angle and the assumed source spectra (which are unknown since the HRC-I does not currently allow to extract energy information). Therefore, the count rates

³ Available from <http://cxc.harvard.edu/toolkit/pimms.jsp>

Table 2. The X-ray binaries detected during our observations.

Source name	In FOV of frame	Offset ^a (')	Coordinates			Count rate ^b (counts s ⁻¹)	Comment
			RA	Dec	Error (") ^c		
1E 1743.1–2843	GC-1	6.6	17 46 21.094	–28 43 42.3	1.1	0.247 ± 0.007	Persistent X-ray binary
	GC-2	18.5					
1A 1742–294	GC-9	11.1	17 46 05.201	–29 30 53.3	1.3	0.84 ± 0.01	Persistent neutron star low-mass X-ray binary Burst detected during GC-10
	GC-10	20.6					
GRS 1741.9–2853	GC-2	9.9	17 45 02.385	–28 54 50.2	1.5	0.267 ± 0.008	Neutron star faint X-ray transient
	GC-7	15.9					
	ACIS-I	6.9	17 45 02.350	–28 54 49.9	1.2	0.269 ± 0.008	
XMM J174457–2850.3	GC-7	11.4	17 44 57.440	–28 50 20.3	1.5	0.337 ± 0.009	Very faint X-ray transient
	GC-2	13.6					
	ACIS-I	7.0	17 44 57.451	–28 50 21.1	2.1	0.0064 ± 0.0015	
Possible VFXT	GC-3	8.7	17 47 37.671	–29 08 09.6	2.5	0.007 ± 0.002	Transient nature needs confirmation

^a Offset between the source position and the pointing position.

^b Count rates are for the full *Chandra*/HRC-I energy range (0.08–10 keV) or the 0.3–7 keV energy range for the *Chandra*/ACIS-I; they are background corrected, but are not corrected for offset.

^c The errors on the coordinates are calculated using equation 5 in Hong et al. (2005) with the addition of a 0.7'' pointing uncertainty, corresponding to 95% confidence levels.

we quote are the uncorrected count rates and are therefore lower limits to the count rates the sources would have if they were located on-axis. Depending on the off-axis angles and the source spectra, the on-axis count rates could have been larger by a factor of a few. Again, if the sources were detected in multiple observations, we only give the count rates from the data set in which the sources had the smallest offset to minimize the systematic errors on the derived fluxes.

4. Results

In total we have detected 21 sources so far. Two sources (the Sgr A* complex and the Arches cluster) are known to embody a complex of point sources in combination with strong diffuse emission (Muno et al. 2003a; Yusef-Zadeh et al. 2002). The analysis of these complex regions is still in progress. Ten of the remaining sources can be identified with known stars (e.g., HD 316314, HD 316224, HD 161274, TYC 06840-38-1, ALS 4400; Fig. 2 left) or have clear counterparts in the Digital Sky Survey images indicating that they are foreground objects (and hence have relatively low X-ray luminosities). We will not discuss the detections of the foreground objects further in this paper, instead we will focus on the detected X-ray binaries.

4.1. The persistent sources

We detected the two persistent X-ray binaries known to be present in the surveying region: 1E 1743.1–2843 and 1A 1742–294.

4.1.1. 1E 1743.1–2843

1E 1743.1–2843 is a persistent X-ray binary for which the type of accreting object is not yet known. The source was in the

FOV of two of the seven HRC-I pointings and was detected during both observations but we detected no bursts from the source. The position obtained from our *Chandra*/HRC-I data is consistent with that derived from a previous *XMM-Newton* observation (Porquet et al. 2003) although, due to the systematic uncertainties in our positional errors, it cannot currently be determined if our position is better than the *XMM-Newton* one. We used PIMMS to convert the obtained count rate (see Table 2). We assumed an absorbed power-law model similar to what was found by Porquet et al. (2003) when fitting the *XMM-Newton* observation of the source (they obtained an equivalent hydrogen column density N_H of $2 \times 10^{23} \text{ cm}^{-2}$ and a photon index of 1.8). This results in unabsorbed fluxes of 1.8×10^{-10} (2–10 keV) and $3 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.5–10 keV) and X-ray luminosities of 1.4 and $2.3 \times 10^{36} \text{ erg s}^{-1}$, respectively. These X-ray luminosities are very similar to what has been seen before for this source (e.g., Porquet et al. 2003).

4.1.2. 1A 1742–294

1A 1742–294 is a persistent X-ray binary harboring a neutron-star accretor as evidenced by the type-I X-ray bursts observed from this system (see, e.g., Pavlinsky et al. 1994). We detected this source during both HRC-I pointings in which the source was in the FOV. During the GC-10 pointing we detected an X-ray burst. Our *Chandra* position is fully consistent with the best position so far reported on this source (using *ROSAT*; Sidoli et al. 2001) and despite the possible unknown systematic uncertainty in our errors, our position is better. We again used PIMMS to convert the obtained count rate (see Table 2) and used the absorbed power-law model ($N_H \sim 6 \times 10^{22} \text{ cm}^{-2}$; photon index ~ 1.8) found when fitting the *BeppoSAX* and *ASCA* data of the source (Sidoli et al. 1999; Sakano et al. 2002). This results in unabsorbed fluxes of 2.3×10^{-10} (2–10 keV) and

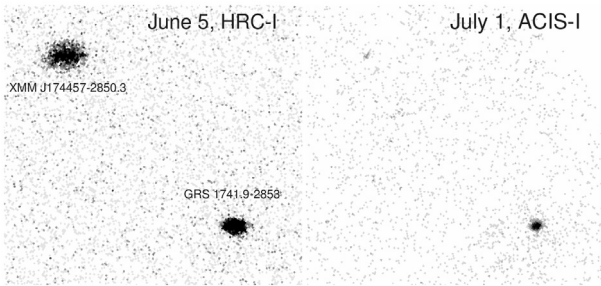


Fig. 3. *Left panel:* the *Chandra*/HRC-I image of XMM J174457–2850.3 and GRS 1741.9–2853 as obtained on June 5, 2005 (field GC-2), *Right panel:* the *Chandra*/ACIS-I image of both sources obtained on July 1, 2005. To show the two sources most clearly we have rebinned the images to a resolution of $\sim 2''$. The apparent extended nature of the sources is due to their relatively large offset positions with respect to the pointing direction of the satellite.

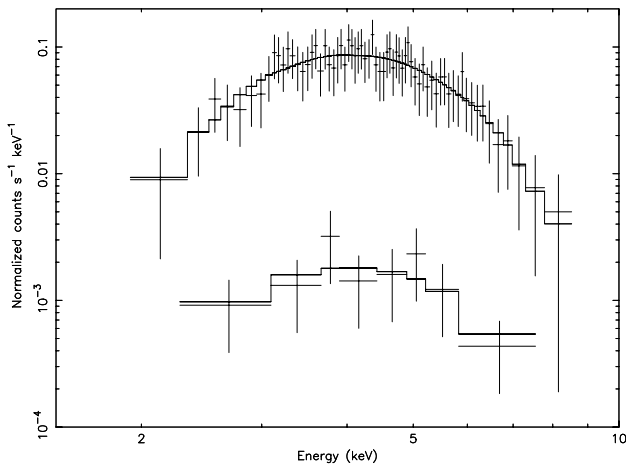


Fig. 4. The spectra of GRS 1741.9–2853 (*top graph*) and XMM J174457–2850.3 (*bottom graph*). The solid lines through the data points indicate the best absorbed power-law fit to the data. Before fitting, the data points of GRS 1741.9–2853 were rebinned so that each bin has 15 counts. The data of XMM J174457–2850.3 were fitted without any rebinning but for display purposes that data in the figure are rebinned to 3 counts per bin.

$3.7 \times 10^{-10} \text{ erg cm}^{-2} (0.5\text{--}10 \text{ keV}) \text{ s}^{-1}$. The corresponding X-ray luminosities are 1.8 and $2.8 \times 10^{36} \text{ erg s}^{-1}$, consistent with what has been observed before for this source (e.g., Sidoli et al. 1999).

4.2. The transient sources

Two transients were clearly visible during our observations: GRS 1741.9–2853 and XMM J174457–2850.3. We made a preliminary announcement of the detection of these new outbursts on 6 June 2005 (Wijnands et al. 2005). Following these detections, we obtained an additional *Chandra* observation of both sources (using the ACIS-I detector) on 1 July 2005 (see Table 1 for details). Because the two transients were only $\sim 4.6'$ away from each other, we could observe both sources with only one ACIS-I pointing. We placed both sources at an off-axis angle of $7'$ in order to limit pile-up in case the sources were as bright as seen during the HRC-I observations. The ACIS-I

data were also analyzed using CIAO and the standard threads. Again, all data could be used since no episodes of high background emission occurred during our observation.

4.2.1. GRS 1741.9–2853

GRS 1741.9–2853 is a neutron star X-ray transient (it exhibits type-I bursts; e.g., Cocchi et al. 1999) which has been detected several times in outburst since its original discovery in 1990 (Sunyaev 1990). Its peak luminosity is typically a few times $10^{36} \text{ erg s}^{-1}$ making it a faint X-ray transient (see Munro et al. (2003b), for more details). This source was detected during two of our pointings (Table 2) but we detected no bursts. The position of the source was consistent with, but not better than the one obtained by Munro et al. (2003b). The observed count rate was converted into fluxes using PIMMS and assuming an absorbed power-law with $N_{\text{H}} = 9.7 \times 10^{22} \text{ cm}^{-2}$ and a photon index of 1.88 (Munro et al. 2003b). This results in unabsorbed fluxes of $1.1 \times 10^{-10} (2\text{--}10 \text{ keV})$ and $1.8 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} (0.5\text{--}10 \text{ keV})$, yielding X-ray luminosities of 0.8 and $1.4 \times 10^{36} \text{ erg s}^{-1}$, respectively (for comparison with previous *Chandra* data on this source reported by Munro et al. (2003b), we also list the 2–8 keV luminosity of $7.0 \times 10^{35} \text{ erg s}^{-1}$). GRS 1741.9–2853 was also detected during the additional *Chandra*/ACIS-I observation (Fig. 3). We extracted the source spectrum using a source extraction region of $10''$ and a background extraction circle of $50''$ from a source-free region close to GRS 1741.9–2853. The spectrum was rebinned to have at least 15 counts per bin to allow the χ^2 fitting method. The resulting spectrum is shown in Fig. 4. We used XSPEC to fit the spectrum and the fit results obtained are listed in Table 3. Clearly, the source flux had decreased by almost an order of magnitude within about a month (i.e., since 5 June 2005). The long-term light curve of the source is plotted in Fig. 5 showing the multiple outbursts of the source in the last 15 years.

4.2.2. XMM J174457–2850.3

XMM J174457–2850.3 is also clearly detected during our HRC-I observations (Fig. 2). This source has been detected only once before in outburst in 2001 (using *XMM-Newton*; Sakano et al. 2005). During that outburst the source was seen at a peak luminosity of $5 \times 10^{34} \text{ erg s}^{-1}$, justifying a classification as a VFXT. We detected it during two of our pointings (Table 2) but saw no bursts. Our source position is consistent with that obtained by Sakano et al. (2005), although the exact uncertainty on our HRC-I position is currently unclear. However, the source was also detected during our additional ACIS-I observation yielding a more reliable position even though the source was relatively weak (see Table 2). This position is significantly better than the *XMM-Newton* one. The observed HRC-I count rate was converted into fluxes using PIMMS and assuming an absorbed power-law with $N_{\text{H}} = 6 \times 10^{22} \text{ cm}^{-2}$ and a photon index of 1.0 (Sakano et al. 2005). This resulted in unabsorbed fluxes of $1.1 \times 10^{-10} (2\text{--}10 \text{ keV})$ and $1.3 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} (0.5\text{--}10 \text{ keV})$ and in X-ray

Table 3. Spectral results for GRS 1741.9–2854 and XMM J174457–2850.3.

Parameter	GRS 1741.9–2854	XMM J174457–2850.3
N_{H} (10^{22} cm^{-2})	$10.5^{+4.9}_{-3.7}$	6^a
Photon index	$1.8^{+1.0}_{-0.8}$	1.3 ± 1.1
Flux ($10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, unabsorbed)		
0.5–10.0 keV	37^{+93}_{-14}	$0.5^{+0.4}_{-0.5}$
2.0–10.0 keV	22^{+10}_{-3}	$0.4^{+0.2}_{-0.4}$
2.0–8.0 keV	17^{+12}_{-3}	$0.3^{+0.1}_{-0.3}$

^a Parameter fixed to the value found by Sakano et al. (2005).

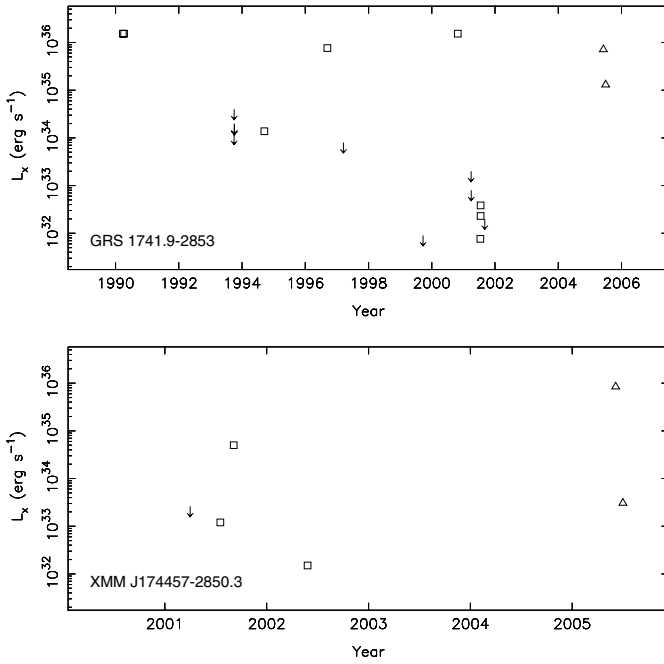


Fig. 5. The light curves of GRS 1741.9–2853 (*top panel*) and XMM J174457–2850.3 (*bottom panel*). In both panels, the triangles indicate the new data reported in this paper. In the top panel, the squares and the upper limits are taken from Muno et al. 2005a (see this paper for the exact energy ranges for each point; our *Chandra* luminosities are for 2–8 keV). In the bottom panel, the squares and the upper limit are from Sakano et al. 2005 and all luminosities are for 2–10 keV.

luminosities of 0.8 and $1.0 \times 10^{36} \text{ erg s}^{-1}$, respectively. This is significantly brighter than what was previously found for the source and makes it a borderline case as a VFXT. As stated above, XMM J174457–2850.3 was also detected during the additional *Chandra*/ACIS-I observation (Fig. 3). We extracted the source spectrum using a source extraction region of $5''$. Due to the rather low number of source photons (26 counts in the 0.3–7.0 keV energy range) we did not rebin the spectrum or subtract the background (which was <0.3 photon in the source region and therefore negligible) so that we could use the Cash statistics (Cash 1979) when fitting the spectrum in XSPEC. The fit results obtained for this observation are also listed in Table 3 and the resulting spectrum is shown in Fig. 4. Clearly, the source flux had decreased by nearly three orders of magnitude within approximately a month (i.e., since

5 June 2005). The long-term light curve of the source is plotted in Fig. 5.

4.2.3. A possible new VFXT

None of the other known transients in the FOV of our observations (see Table A.1) were conclusively detected in our HRC-I data. The upper limits on their luminosities depend strongly on their spectral shape and their off-axis positions, with a rough estimate of $\sim 10^{34} \text{ erg s}^{-1}$. Several additional weak sources were detected during our observations which could not be identified with a star in the Digital Sky Survey database. Only one of these had a large enough count rate (see Table 2) that its X-ray luminosity exceeded $10^{34} \text{ erg s}^{-1}$ if it had a “prototypical X-ray binary” spectrum (power-law model with photon index of 1.8 and a typical N_{H} of $6 \times 10^{22} \text{ cm}^{-2}$). Using such a spectral shape, the source had unabsorbed X-ray fluxes of 1.9 and $3.1 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for 2–10 keV and 0.5–10 keV, respectively, and thus luminosities of $1.5 \times 10^{34} \text{ erg s}^{-1}$ (2–10 keV) and $2.4 \times 10^{34} \text{ erg s}^{-1}$ (0.5–10 keV). We note that we do not know the intrinsic source spectrum and therefore these fluxes and luminosities could be significantly off if the real source spectrum is considerably different. We investigated the *Chandra* and *XMM-Newton* archives and found that the source was in the FOV of one previous *XMM-Newton* observation. The source was not detected during this *XMM-Newton* observation, but it was at the edge of its FOV making it difficult to obtain a reliable upper limit on the flux, especially because we do not know the spectral shape of the source. We estimate that the luminosity of the source was at least a factor of a few fainter during the *XMM-Newton* observation compared with our HRC-I data. Although this is suggestive of a transient nature for this source, it could also be a highly variable persistent source. Currently, we will refer to this source as a possible new VFXT.

4.2.4. Observations at other wavelengths

We obtained VLA observations at 4 and 6 cm on 8–9 June 2005 of GRS 1741.9–2853, XMM J174457–2850.3, and the possible new VFXT. The analysis of these radio data is complicated by the strong side-lobes of Sgr A* and we are still in the process of fully analyzing these data. A preliminary analysis of the 4 cm data shows that none of the sources were conclusively detected with radio fluxes of 0.003 ± 0.060 , -0.002 ± 0.046 ,

and 0.032 ± 0.043 mJy/beam, respectively. On 8 June 2005, Laycock et al. (2005) obtained *I*-band images of GRS 1741.9–2853 and XMM J174457–2850.3 using the Magellan-Baade telescope but could not detect the *I*-band counterparts of the sources. This is not surprising when considering the high absorption column in front of both sources.

5. Discussion

We have presented our initial results of the first observations taken as part of our *XMM-Newton/Chandra* monitoring campaign of the inner region of our Galaxy. Using our *Chandra*/HRC-I observations we detected mostly foreground objects (like X-ray active stars), but we also detected two persistent X-ray binaries, two X-ray transients, and one possible very faint X-ray transient (but its transient nature requires further confirmation). Clearly, our monitoring *XMM-Newton/Chandra* campaign is detecting transients in outburst which are being missed by the other monitoring instruments in orbit. Our campaign therefore complements, as designed, other monitoring campaigns using satellites currently in orbit (e.g., Levine et al. 1996; Swank & Markwardt 2001; Revnivtsev et al. 2004; Kuulkers et al. 2005). These programs find mainly the brighter transients or the faint transients far away from the crowded fields near Sgr A*.

The faint X-ray transient GRS 1741.9–2853 was detected at a level of $\sim 10^{36}$ erg s^{−1}, very similar to what has been observed previously for this source. A month after our initial HRC-I observations this source could still be detected at $\sim 10^{35}$ erg s^{−1} with the ACIS-I. The parameters obtained for the source spectrum during this observation were consistent with those found by Munro et al. (2003b) when the source was an order of magnitude brighter, indicating that the source spectrum is not very dependent on source luminosity. Although we did not detect X-ray bursts during our observations, this source is known to exhibit such phenomena making it very likely to be a neutron star accreting from a low-mass companion star. Even though no optical/infrared counterpart has so far been found for this source, type-I X-ray bursts have only been seen for low-mass X-ray binaries making it very likely that GRS 1741.9–2853 is also such a system. The fact that GRS 1741.9–2853 harbors a neutron star also is consistent with the non-detection of the source in our radio data since neutron-star low-mass X-ray binaries are known to exhibit very low radio luminosities (e.g., Fender & Kuulkers 2001; Munro et al. 2005b).

Figure 5 shows that the source has been seen to be in outburst at least 5 times with X-ray luminosities above 10^{34} erg s^{−1}. Its recurrence time can be estimated to be between 2 and 5 years, making GRS 1741.9–2853 one of the most active transients in our FOV, with a duty cycle of about 50% (as estimated from Fig. 5)⁴. Its peak luminosity is very similar to the accreting millisecond X-ray pulsar

SAX J1808.4–3658. For that system and the other accreting millisecond X-ray pulsars, it has been suggested that their pulsating nature is related to their rather low time averaged accretion rates (e.g., Cumming et al. 2001). Although the time averaged accretion rate of GRS 1741.9–2853 seems to be higher than for the accreting millisecond pulsars due to its higher duty cycle, GRS 1741.9–2853 could still be a millisecond X-ray pulsar as well (see also Munro et al. 2003b), especially if its duty cycle has been overestimated (see footnote 4). Unfortunately, its faintness and its location in the Sgr A* region make it very difficult to detect these pulsations using *RXTE* because of significant contribution to the detected count rate from other sources in the FOV. However, with *XMM-Newton* pulsations could be detected within several tens of ksec (depending on the actual fluxes of the source) if they have similar strengths as the pulsations seen in the known accreting millisecond pulsars.

The VFXT XMM J174457–2850.3 was also detected during our HRC-I observations at an X-ray luminosity close to 10^{36} erg s^{−1}. This is about a factor of 20 higher than what was previously seen for this source (Sakano et al. 2005). This demonstrates that VFXTs can exhibit a large range of X-ray luminosities (similar to what has been observed for the brighter systems) and XMM J174457–2850.3 is at the border between faint and very faint X-ray transients, clearly demonstrating that our luminosity boundaries are somewhat arbitrary as discussed in the introduction. It is possible that the previous detection of this source was made either during the rise or decay of a full outburst and that the maximum luminosity reached at the time was closer to what we have observed for the source during our HRC-I observations. Within a month the source luminosity has decreased by nearly 3 orders of magnitude. Its X-ray spectrum at this low X-ray luminosity was consistent with that found by Sakano et al. 2005 demonstrating that for this source the shape of its spectrum is not strongly dependent on luminosity for luminosities below 5×10^{34} erg s^{−1}. Since we cannot extract any spectral information from the HRC-I data we cannot determine if the spectrum was significantly different at times when the source had X-ray luminosities close to 10^{36} erg s^{−1}. Since only very few observations have been performed of this source (see Fig. 5), it is difficult to estimate its recurrence time (at most of order 3 years according to Fig. 5) and its time-averaged accretion rate. The non-detection at radio wavelengths might indicate that the source harbors a neutron-star accretor since according to the radio-X-ray correlation found for low luminosity black hole binaries (Gallo et al. 2003) the source should have had (if it harbors a black-hole accretor which was accreting at $\sim 10^{36}$ erg s^{−1}) a radio flux of ~ 1 mJy, significantly higher than our radio upper limit. Alternatively, XMM J174457–2850.3 could still harbor a black hole, but one which does not follow this correlation.

We did not detect any unambiguous new VFXTs during our observations, although we detected a possible new VFXT whose transient nature must be confirmed. This will be possible with our next sets of monitoring observations. Our three

⁴ We note that this is likely an upper limit on the duty cycle since actual source detections are more frequently reported in the literature than non-detections which will skew the data toward detections. For example, the data presented by Munro et al. (2003b) of GRS 1741.9–2853 (as used in Fig. 5) does not report the non-detections of the source as seen with *ROSAT* (Sidoli et al. 2001) or

BeppoSAX (Sidoli et al. 1999; using the Narrow Field Instruments). Since no upper limits on the source flux are given in these papers, we also do not include these non-detections in Fig. 5.

additional epochs will also be very important to find further VFXTs, either previously unknown transients or recurrent ones. Our observations will allow us to set tighter constraints on the time averaged accretion rates of these systems than is currently possible with the available data. Such constraints are especially important for the low-mass X-ray binaries among the VFXTs because if their time-averaged accretion rates is very low then our theories of the evolution of such systems will have a very hard time explaining their existence without invoking exotic scenarios such as accretion from a brown dwarf or planet or intermediate mass black hole accretors (e.g., King & Wijnands 2006). The latter option cannot be invoked if type-I X-ray bursts have been observed for these systems since this establishes the existence of a neutron star accretor. Potential candidates for such systems are the burst-only sources mentioned in the introduction. Monitoring observations of these sources with sensitive X-ray telescopes would be very useful to constrain their time-averaged accretion rates to determine if indeed these rates are very low for these systems.

Finding new VFXTs and determining their time averaged accretion rate using our monitoring campaign is only one way forward to increase our understanding of these enigmatic transients. We now discuss other avenues that can be explored as well to achieve that goal. First, a search in the data archives for previously unnoticed VFXTs (e.g., by comparing different exposures of the same fields) might lead to the detection of several more systems. Second, larger regions of our Galaxy need to be monitored at the desired sensitivity to detect the low fluxes observed from VFXTs. It is especially important to determine if a large number of VFXTs also exist outside the inner region of our Galaxy. Munro et al. (2005a) found that the excess of VFXTs within 10 arcmin of Sgr A* is significant and might point to an unusual formation history of these systems. However, if a large number of VFXTs are also found further away from Sgr A* (e.g., systems like XMM J174716–2810.7 or SAX J1828.5–1037; Sidoli & Mereghetti 2003; Hands et al. 2004), then any production mechanism which requires the high stellar density near Sgr A* cannot be invoked for these VFXTs. There is currently no monitoring satellite in orbit which can perform that task mainly due to a lack of sensitivity and angular resolution of the instruments. However, it is possible to derive a first approximation to the number density of VFXTs at large distances from the center of a spiral galaxy by performing several deep pointings of the core of other spiral galaxies. The most obvious choice is the nearest large spiral galaxy to our own, M31. Within a ~250 ks exposure it is possible to observe a $3.7 \text{ kpc} \times 3.7 \text{ kpc}$ region of M31 using the *Chandra*/ACIS-I detector with a limit sensitivity of $1\text{--}4 \times 10^{34} \text{ erg s}^{-1}$ (depending on the spectral properties of the sources). Several such deep pointings would detect all but the faintest X-ray transients in a large region of M31. Alternatively, such programs can also be performed for the smaller spiral galaxy M33 or for galaxies further away. In the latter case, the limiting sensitivity will be of course less.

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Online Material

Appendix A: Distribution of transients in the FOV

In Table A.1 we have listed the known X-ray transients and persistent X-ray binaries which are in the FOV of our *XMM-Newton* and *Chandra* monitoring observations. This table also shows the distance of the sources with respect to Sgr A* and the maximum reported X-ray luminosity for these sources as found in the literature. We have converted the luminosities to the 2–10 keV energy range using the reported spectral parameters of the sources. From this table and from Fig. A.1 it can clearly be seen that only one bright to very bright transient is present (1A 1742–289) within a distance of $<15'$ from Sgr A*, but eight VFXTs⁵ and two faint X-ray transients (although the two faint transients are just barely brighter than 10^{36} erg s⁻¹ and they could just be the brightest VFXTs in the FOV). Clearly, the number of VFXTs within $15'$ of Sgr A* is significantly larger than that of the brighter transients. When extending the region out to $25'$, we see eight VFXTs, three faint transients and only 3 bright to very bright transients. Note, however, that the region $>10'$ away from Sgr A* has been less sampled with sensitive X-ray instruments than closer to Sgr A*, meaning that the number of VFXTs within $25'$ of Sgr A* is likely to grow thanks to our monitoring program.

This strongly suggests that the number density of VFXTs is indeed significantly higher than that of the brighter transients. The fact that the brighter systems were until recently much easier to detect than the fainter systems means that this discrepancy in number densities will only become larger in the future. However, one VFXT (CXOGC J174540.0–290031) and one faint transient (AX J1745.6–2901) have exhibited eclipses and there is strong evidence (Muno et al. 2005) that at least CXOGC J174540.0–290031 was intrinsically much brighter ($>10^{36}$ erg s⁻¹) than what we observe because the inner part of the system is blocked from our line of sight and we only observe the scattered (e.g., in a corona) X-ray emission from the system, making it artificially seem very faint. One can argue that this holds true for the other eclipsing source and possibly for all VFXTs for which we have not yet observed the eclipses or the X-ray dips associated with high inclination. If we conservatively assume that sources with inclinations in the range of 60° – 90° could appear as VFXTs, then a random distribution of orbital inclinations should give roughly equal numbers of bright transients and VFXTs (see also King & Wijnands 2006; the solid angle is proportional to the cosine of the inclination). Clearly, the distribution of observed transients in the FOV of our monitoring campaign (see Table A.1) shows a lack of brighter systems, even when also considering the two persistent X-ray binaries.

Moreover, strong evidence exists that for the known dippers and eclipsing X-ray binaries in other parts of the

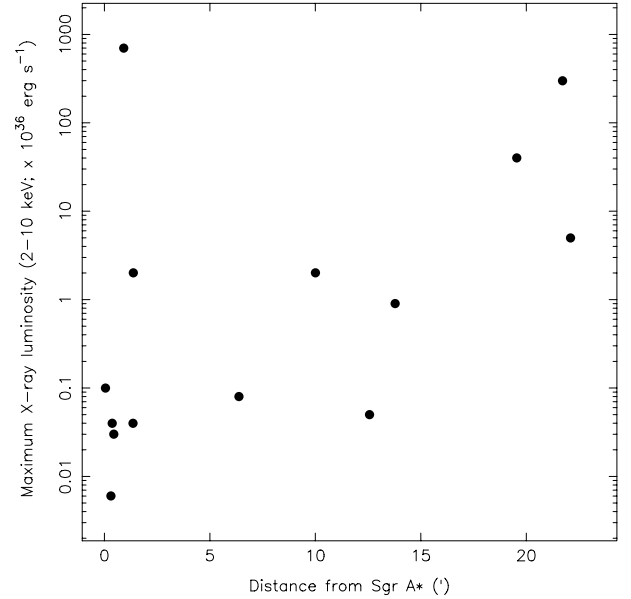


Fig. A.1. The observed maximum X-ray luminosities (2–10 keV) of the X-ray transients in our FOV as a function of the distance of the transients to Sgr A*.

Galaxy we *do* directly look at the inner part of the systems and not just indirectly via scattering (e.g., due to the detection of kHz QPOs or nearly coherent oscillations during type-I X-ray bursts in several high inclination sources; e.g., Boirin et al. 2000; Homan & van der Klis 2000; Wijnands et al. 2001; Galloway et al. 2001). Therefore, the observed X-ray luminosity is indeed the intrinsic luminosity of these systems. Only for the so-called accretion-disk-corona sources (which have the highest inclination of all systems) do we have evidence that only the scattered emission is seen making these systems appear fainter than they are intrinsically. The inclination range for such sources is significantly smaller than what we used above, thus making the problem even worse. Clearly, it is very likely that most of the VFXTs do not appear very faint as a result of inclination effects but rather that they are intrinsically very faint.

The fact that VFXTs seem to be overabundant close to the Galactic center compared to brighter systems might also have consequences for certain types of models for the VFXTs. For example, King & Wijnands (2006) discussed briefly the possibility that the VFXTs harbor neutron stars and black holes which accrete from the weak wind of low-mass companion stars resulting in very faint outbursts. However, they argued that these systems must eventually evolve into brighter states because the companion stars will fill their Roche lobes at a certain time in the future. If indeed, as they suggested, these brighter states have longer durations than the wind accreting states, then the lack of brighter systems present among the very faint ones would suggest that this model cannot explain the nature of the VFXTs.

⁵ The VFXT CXOGC J174535.5–290124 is located in the error circle of the faint transient and eclipsing source AX J1745.6–2901. It is possible that both sources are the same one, which would reduce the number of VFXTs to seven although this would not affect the conclusions in this appendix. However, no eclipses were found for CXOGC J174535.5–290124 in the *Chandra* data available for this source (M. Muno 2005, private communication), making it less likely that both sources are the same one.

Table A.1. Persistent and transients X-ray binaries in the FOV of our observations.

Source name	Distance from Sgr A* (')	Maximum luminosity ^a (erg s ⁻¹)	Classification	Comment	Reference ^b
Transient sources					
CXOGC J174540.0-290031	0.05	1×10^{35}	very faint	eclipser, radio counterpart	1
CXOGC J174541.0-290014	0.31	6×10^{33}	very faint		1
CXOGC J174540.0-290005	0.37	4×10^{34}	very faint		1
CXOGC J174538.0-290022	0.44	3×10^{34}	very faint		1
1A 1742-289	0.92	7×10^{38}	very bright	radio counterpart	2
CXOGC J174535.5-290124 ^c	1.35	4×10^{34}	very faint		1
AX J1745.6-2901	1.37	2×10^{36}	faint	burster, eclipser	3
CXOGC J174554.3-285454	6.38	8×10^{34}	very faint		1
GRS 1741.9-2853	10.00	2×10^{36}	faint	burster	4
XMM J174544-2913.0	12.56	5×10^{34}	very faint		5
XMM J174457-2850.3	13.78	9×10^{35}	very faint		6
SAX J1747.0-2853	19.55	4×10^{37}	bright	burster	7
GRO J1744-28	21.71	3×10^{38}	bright	X-ray pulsar	8
KS 1741-293	22.09	5×10^{36}	faint		9
Persistent sources					
1E 1743.1-2843	18.99	3×10^{36}	faint		10
1A 1742-294	30.95	1×10^{37}	bright	burster	11

^a These maximum observed luminosities are taken from the references and converted to a 2–10 keV luminosity for a distance of 8 kpc.^b References: 1: Muno et al. 2005a; 2: Branduardi et al. 1976; 3: Maeda et al. 1996; 4: Muno et al. 2003b; 5: Sakano et al. 2005; 6: this paper; 7: Werner et al. 2004; 8: Giles et al. 1996; 9: In 't Zand et al. 1991; 10: Cremonesi et al. 1999; 11: Sakano et al. 2002.^c This source is located in the error circle of AX J1745.6–2901 and it is possible that both are the same source. However, no eclipses were found for CXOGC J174535.5–290124 in the *Chandra* data available for this source (M. Muno 2005, private communication) making this identification less likely.